Exploring with PAM:

Prospecting ANTS Missions for Solar System Resource Survey

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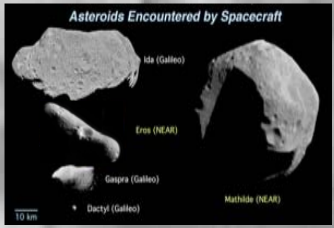
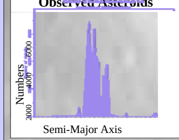
Introduction. ANTS (Autonomous Nano-Technology Swarm), a large (1000 member) swarm of nano to picoclass (10 to 1 kg) totally autonomous spacecraft, are being developed as a NASA advanced mission concept [1, 2]. ANTS, based on a hierarchical insect social order, use an evolvable, self-similar, hierarchical neural system in which individual spacecraft represent the highest level nodes. ANTS uses swarm intelligence attained through collective, cooperative interactions of the nodes at all levels of the system. At the highest levels this can take the form of cooperative, collective behavior among the individual spacecraft in a very large constellation. The ANTS neural architecture is designed for totally autonomous operation of complex systems including spacecraft constellations. The ANTS (Autonomous Nano Technology Swarm) concept has a number of possible applications. A version of ANTS designed for surveying and determining resource potential of the asteroid belt, called PAM (Prospecting ANTS Mission), is examined here. Related mission concepts are also discussed.



Distribution of Observed Asteroids



Mainbelt Asteroids. What do we know?

Located between the orbits of Mars and Jupiter (2.1 to 3.3 AU)

A few hundred thousand to a couple million >1 km diameter objects

Surface of largest 1000 observed asteroids ~ surface area of Mars

Refractory and more differentiated silicates dominate inner belt

Volatile and primitive materials are abundant in outer belt

Observations are available for a closer, brighter, larger fraction:
- Orbit determinations for 100,000
- Spectral analysis for a few thousand
- Shape models for 10

PAM Mission Context

PAM is consistent with the present strategic plan for the NASA mission and the HEDS (Human Exploration and Development of Space) enterprise.

PAM generates a breakthrough in completing the called-for survey of the solar system and automated discovery of space resources envisioned as building blocks for expanding the human presence in space.

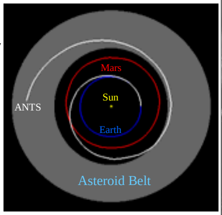
PAM does this by providing measurements of a representative cross-sections of the mainbelt asteroid population to determine:

- What is the nature of smaller, darker, more remote asteroids more difficult to observe from Earth?
- How are elements, minerals, rocks distributed in small bodies and their parent bodies in space and time?
- What is the relationship between 'space weathering', regolith, underlying rock, and the original parent body material for asteroids?
- What are the distributions and effective limits for compositional and dynamic properties?

Completed and Started Mission Milestones in Asteroid Exploration: NEAR and Dawn

PAM Solar Sail Trajectory

- Solar sail size: 100 m^2
- S/C Mass: 1 kg
- Normal from sun line: 30°
- Transfer to: 2.8 AU
- Transfer time: 3.5 yr.
- da/dt~100 Mm/12 hrs.



Near Term Benefits

This concept could be tested with small numbers of prototypes for a near-Earth target.

Low periapsis orbiters in vertical or planar array clusters could investigate a variety of problems for the Moon or Mars.

Such homogeneous (identical sensors) or heterogeneous (multiple sensors) experiments would allow near real time analysis of the machine/human interface.

In homogeneous mode, ANS could be flown in formation (to maintain consistent inter-sensor orientation) for 3D analysis of magnetic or gravitational field anomalies, or temporal/spatial variations in magnetospheres or ionospheres.

In heterogeneous mode, ANTS could be flown in conjunction (to create comparable inter-sensor ground coverage) for ground site characterization and determination of resource inventories.

The Challenges:	The Solution:
Large number of bodies or extensive terrain.	An insect colony analog (Worker, Messenger, Leader).
Wide variety of instruments with different operational requirements.	Large number of very small, very specialized spacecraft.
Inaccessible and/or remote terrain.	Solar sails for Delta V.
Comparatively large Delta V requirement for 'fully loaded'	Highly autonomous operation.

PAM Breakthrough in Exploration:

Single Sensor/Multi-spacecraft missions are uniquely capable of providing comprehensive asteroid survey.

Ground based or even Earth orbiting observatories, even with projected improvements in sensitivity, will be not be able to provide measurements for more remote, smaller, or darker asteroids, which must be observed by spacecraft.

Multi-sensor/Single spacecraft missions, such as NEAR, are useful in providing extensive documentation for one to a handful of previously observed asteroids, but are not designed for surveying a wide range of unexplored asteroids.

Essential sensors, such as imagers, spectrometers, and altimeters, have very different optimal operational requirements for a) illumination conditions, b) pointing geometry, c) distance to target, and d) orbital configuration.

As a result, constant compromising to meet sensor requirements and results in less efficient collection of high quality data, a problem that is magnified when a small, irregularly shaped object, such as an asteroid, is being explored.

The ANTS/PAM concept calls for a fleet of single sensor spacecraft, working individually or as teams. Individual spacecraft can be flown to meet optimal instrument operational as well as science requirements simultaneously.

PAM specialized sensor/multiple spacecraft concept lends itself to asteroid exploration. Targeting thousands of widely separated bodies, which will require tracking a highly target, demands autonomous constellation of specialized workers

AUTONOMOUS NANOTECHNOLOGY SPACECRAFT

Present nanospacecraft extended to picospacecraft regime.

Explorer complete with subsystems to carry out the mission.

On-board computation, AI, heuristics systems.

Autonomous control at all levels.

Solar sail propulsion systems.

Inter-spacecraft communications :

- **Low bandwidth (LBW) for distance, swarm cohesion.**
- **High bandwidth (HBW) for data transfer.**

Types: Leader/Messenger and Worker, both classes built on an autonomous spacecraft architecture providing basic functions (GN&C, ACS…).

PROSPECTING ANTS MISSION CONCEPT

MESSENGER/LEADERS
Enhanced Computation
Enhanced Communication
Enhanced Data Storage
Responsible for mission goals
Provide command & communication network

WORKERS
Science instrument specialists
Responsible for data-taking operations at asteroids
Form 'virtual experiment teams' for encounters

Both classes built on an autonomous spacecraft architecture providing basic functions (C&DH, GN&C, ACS…).

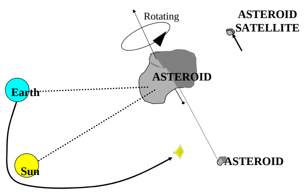
PAM Challenges for Mission Concept

Far from Earth (15-75 minutes 2-way light-travel time)

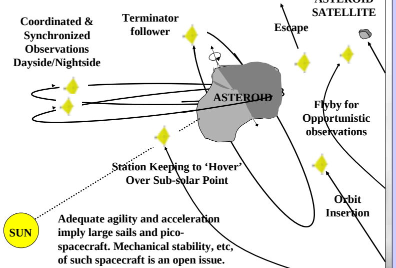
Far from Sun: 2.1-3.5+ AU Solar Constant is < ¼ Earth.

Irregular shape and mass distribution with 100,000's km between asteroids, 100's to study each year.

Characteristics of asteroids must be learned by ANTS during operations.



PAM Encounter Architecture



Probable Scientific Instruments/Operational Requirements

Instrument	Optimal Maneuver/Viewing Requirement
Visible Imaging Spectrometer	Flyby>Hover>Orbit/Full to partial illumination
Ranging Device	Orbit/Nadir-point
Radio Science Experiment	Orbit/Elliptical Orbit
Near IR Spectrometer	Hover at Sub-solar/Full illumination, nadir-point
X-ray Spectrometer	Hover at Sub-solar/Full illumination, nadir-point
Gamma-ray Spectrometer	Hover at Fixed Point/Fill FOV, Close, Boom
Magnetometer	Hover at Fixed Point>Orbit/Close, Boom 111011

PAM Requirements for ANTS

Real time autonomy at every level essential for all aspects of mission.

One month optimal science operations/asteroid and concurrent operations at hundreds of asteroids.

Ongoing evolution of tactics and strategies for instrument deployment as a function of asteroid characteristics.

No single point failure, robust to minor and catastrophic loss.

PAM 'Virtual Experiment Teams'

ANTS could acquire simultaneous coverage of the same target, thus providing a comprehensive set of measurements to solve a particular scientific problem, by forming 'Virtual Experiment Teams' of identical or multiple sensors.

Asteroid Detector/StereoMapper consisting of two wide field imaging spectrometers with enhanced navigational (location and pointing awareness) capability separated by distances varying from hundreds of kilometers to kilometers would be used to detect and determine the orbit of potential targets at a distance, or move to within kilometers of a target to obtain astronomical classification and figure properties and identify candidates for detailed studies.

Dynamic Modeler consisting of an enhanced radio science instrument, altimeter, and wide field imager separated by tens of kilometers to kilometers would be used to acquire detailed figure parameters (including shape model) and dynamic properties (spin, density, mass distribution).

Petrologist consisting of X-ray, Near Infrared, Gamma-ray, Thermal IR, and wide field imager separated by tens of kilometers to kilometers would be used to determine the abundances and distribution of elements, minerals, and rocks present, from which the nature of geochemical differentiation, origin, and history of the object, and its relationship to a 'parent body' could be inferred.

Photogeologist consisting of Narrow Field and Wide Field Imagers and Altimeter separated by tens of kilometers to kilometers which would be used to determine the nature and distribution of geological units based on texture, albedo, color, and apparent stratigraphy as expressed on the surface, from which the nature of the dynamic history and origin of the object could be inferred.

Prospector consisting of altimeter, magnetometer, Near Infrared, and X-ray spectrometers separated by tens of kilometers to kilometers which could be used to determine the distribution of 'resources', including Fe/Ni and volatiles on preselected candidates for 'mining'.